STUDY OF CETANE PROPERTIES OF ATJ BLENDS BASED ON WORLD SURVEY OF JET FUELS

INTERIM REPORT
TFLRF No. 475

by
Nigil Jeyashekar, Ph.D., P.E.
Ed Frame

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
Patsy Muzzell
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD32 Task 2.2)

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Gary Bessee

Gary B. Bessee, Director
U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI®)

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14. ABSTRACT
The cetane properties of a fuel blend containing highly iso-paraffinic ATJ fuel and Jet fuel were studied. Literature review was conducted to obtain cetane properties from PQIS database, CRC report and Tri-Services report. Based on data collected from Task 2.4 of WD0024, on cetane properties of ATJ blends, correlation equations were developed to determine cetane properties as a function of volume percentage of ATJ in the fuel, which was used to determine cetane properties of maximum ATJ blends (50/50 ATJ/Jet fuel). The overall conclusion is that maximum ATJ blends from any jet fuel (Jet A, Jet A-1, and JP-8) had an increase in CI from 7% to 8% using the four variable, D4737 method, while the increase in CI was approximately 3% using D976 method. Based on the extensive decrease in CN and DCN values much below 40, maximum ATJ blends (50/50 ATJ/Jet fuel blends) were deemed not fit-for-use. It was concluded that the amount of ATJ that must be blended with Jet A or JP-8 to obtain 40 DCN, was less than 50% for all the PADD.

15. SUBJECT TERMS
Cetane properties, Cetane Index, Cetane Number, Derived Cetane Number, ATJ Blends, Jet A, JP-8, Jet A-1, Dataset

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EXECUTIVE SUMMARY

The cetane properties of a fuel blend containing highly iso-paraffinic ATJ fuel and jet fuel were studied. Literature review was conducted to obtain cetane properties from the Petroleum Quality Information System (PQIS) database, a Coordinating Research Council (CRC) report and a Tri-Services report. Based on data collected from Task 2.4 of WD0024, on cetane properties of ATJ blends, correlation equations were developed to determine cetane properties as a function of volume percentage of ATJ in the fuel. These equations were used to determine the cetane properties of maximum ATJ blends (50/50 ATJ/Jet fuel) across all the data sets for all PADDs in the CONUS and OCONUS regions to the extent that data is available.

The overall conclusion is that maximum ATJ blends from any jet fuel (Jet A, Jet A-1, and JP-8) had an increase in CI from 7% to 8% using the four variable, ASTM D4737 method, while the increase in CI was approximately 3% using ASTM D976 method. These values were consistent in all the literature datasets, spanning from 2006 to 2014, that were reviewed and examined. Based on the extensive decrease in CN and DCN values much below 40, maximum ATJ blends (50/50 ATJ/Jet fuel blends) were deemed not fit-for-use. Recommendations were made on the volume percentage of ATJ that can be blended in for each PADD region in CONUS region to result in a value of 40, that is deemed fit-for-use in ground equipment, as shown in the Table below. Due to limited data availability, recommendation could not be made for OCONUS region.

PADD Region	Jet A		Jet A		JP-8		JP-8	
	Max vol.% ATJ	DCN	Max vol.% ATJ	CN	Max vol.% ATJ	DCN	Max vol.% ATJ	CN
1	32.00	40.17	30.00	40.03	32.00	40.17	20.00	40.00
2	0.00	39.90	0.00	39.40	47.00	40.09	26.00	40.19
3	48.00	40.19	32.00	40.19	33.00	40.13	22.00	40.10
4	29.00	40.07	15.00	40.04	16.00	40.07	11.00	40.15
5	24.00	40.05	13.00	40.10	35.00	40.13	11.00	40.15

Jet A obtained from PADD 2 is not qualified to make an ATJ blend. For all practical purposes, it was concluded that maximum ATJ blends can be made from PADD 3 for Jet A fuel, and PADD 2 for JP-8 fuel, without greatly compromising the overall combustion quality.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period August 2014 through March 2016 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the TARDEC contracting officer's technical representative. Ms. Patsy Muzzell of TARDEC served as project technical monitor.

The author would like to acknowledge the contribution of the TFLRF technical support staff along with the administrative and report-processing support provided by the TFLRF administrative staff.

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ACRONYMS AND ABBREVIATIONS

%	Percent
ASTM	American Society for Testing and Materials
ATJ	Alcohol-to-Jet
CI	Cetane Index
CN	Cetane Number
CONUS	Contiguous United States
CRC	Coordinating Research Council
DCN	Derived Cetane Number
DoD	Department of Defense
FAME	Fatty Acid Methyl Ester
JP-8	Jet Propellant-8
max.	Maximum
OCONUS	Outside the Contiguous United States
PADD	Petroleum Administration for Defense Districts
PQIS	Petroleum Quality Information System
SwRI	Southwest Research Institute
vol.	Volume
WD	Work Directive
WPFAB	Wright-Patterson Air Force Base

1.0 INTRODUCTION AND OBJECTIVE

The Army desired to study the effect of blending highly iso-paraffinic ATJ (Alcohol-to-Jet) blending stock into JP-8 (Jet Propellant-8) in order to understand the effect of ATJ fuel blends would have on ground vehicle engines and support equipment. As a part of this objective, the following study describes the variation in cetane properties when ATJ is blended into JP-8. More specifically, the objective of the study was to develop formulations for variation in Cetane Index (CI), Cetane Number (CN), and Derived Cetane Number (DCN), as a function of volume percent of ATJ in JP-8, using data obtained from Task 2.2 of WD0024. The goal of this study was to apply these formulations to data available in the literature to determine the CI, CN and DCN values of 50/50 ATJ-JP-8 blends, also known as maximum ATJ blends.

The objective was accomplished by conducting a literature review to collect JP-8, Jet A and Jet A-1 data available worldwide and applying the formulations to obtain cetane properties of 50/50 ATJ-Jet fuel blends. This report presents and compares statistical charts, containing mean, standard deviation and range, between jet fuels and 50/50 ATJ-JP-8 blends, also called as maximum ATJ blends. Weighted statistics are presented to the extent where pertinent data is available for computation of weighted quantities. The study concludes by presenting the maximum volume percentage of ATJ that could be blended with JP-8 to maintain a minimum of 40 for the DCN and CN values.

2.0 LITERATURE REVIEW

The literature review for worldwide data on jet fuel cetane properties was focused on the following sources:

a. Petroleum Quality Information System (PQIS) 2013: Annual Report and Database [1].

b. Coordinating Research Council (CRC) Report No. 647 [2].

c. SwRI Tri-Services Final Report (Project No. 08.17149.36.100) [3].

A detailed review of each literature source and any limitations thereof are described in the subsequent sections.

2.1 REVIEW OF PQIS DATABASE

Department of Defense (DoD) has twelve regions in its worldwide reporting structure. Regions 1 to 5, in Figure 1, are designated as Petroleum Administration for Defense Districts (PADD), which handles the Contiguous United States (CONUS) procurements, while Regions 6 to 12, in Figure 2 are designated to handle procurements Outside the Contiguous United States (OCONUS). Figure 3 provides a detailed breakdown of the 12 worldwide regions by States (for CONUS) and by countries (for OCONUS).

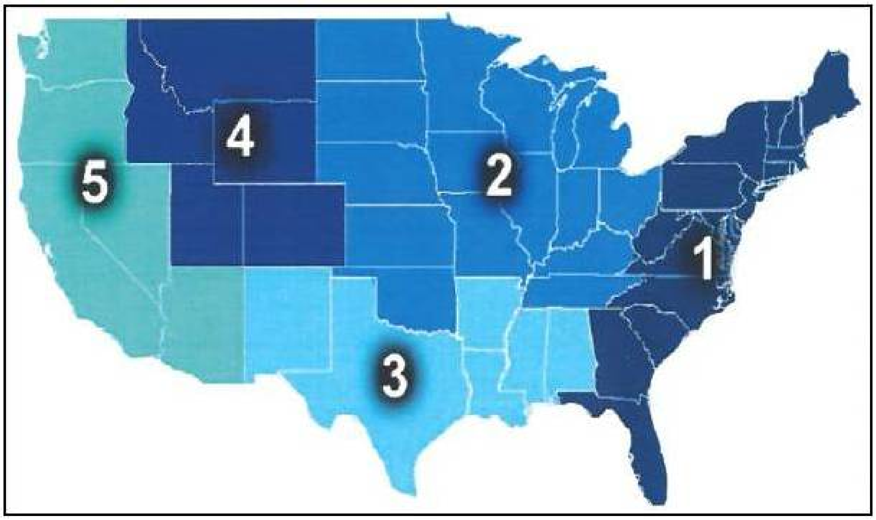

Figure 1. PADD Regions in CONUS [1]

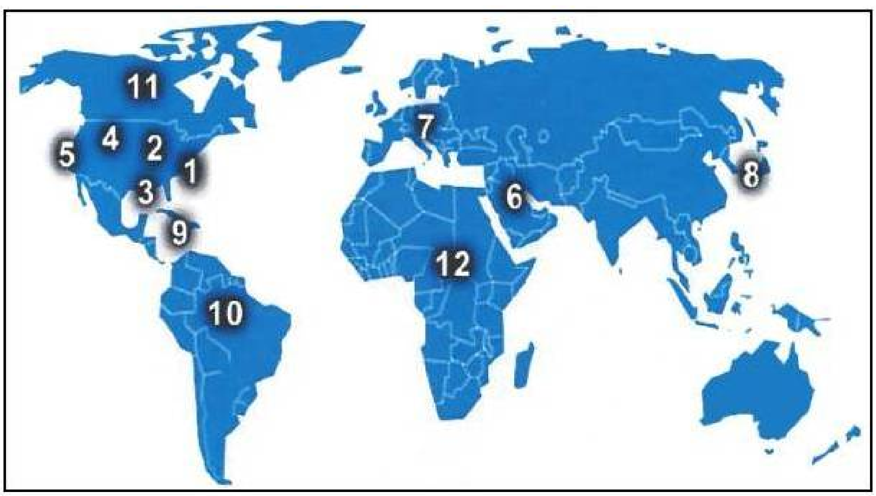

Figure 2. Worldwide Defense Regions [1]

Region	Title	PADD	State or Country
1	East Coast	I	ME, VT, NH, MA, RI, CT, NY, PA, NJ, DE, MD, VA, WV, NC, SC, GA, FL
2	East Central	II	ND, SD, MN, IA, NE, WI, MI, OH, KY, TN, IN, IL, MO, KS, OK
3	Gulf Coast	III	AL, MS, AR, LA, TX, NM
4	West Central	IV	MT, ID, WY, UT, CO
5	West Coast	V	WA, OR, CA, NV, AZ
6	Middle East		Kuwait, Bahrain, Pakistan, United Arab Emirates
7	European		Europe, Israel, Turkey
8	Pacific		Korea, Japan, HI, AK, Australia, Russia, Singapore, China
9	Caribbean		Coastal Aruba, Bermuda, Bahamas, Barbados, British Virgin Islands, Cuba, Dominican Republic, Jamaica, Grand Cayman, Martinique, Puerto Rico, Virgin Islands
10	Central & South America		Belize, Columbia, Curacao, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Peru
11	Canada		Canada
12	Africa		Cape Verde, Ghana

Figure 3. Defense Regions by Country [1]

In the PQIS database, the mean cetane property refers to the sum of test result of all the batch analysis and divided by the total number of batches and the weighted cetane property refers to the volumetrically weighted average of the property, based on volume of jet fuel represented by test values. The following points highlight the summary of literature review and limitations on the published data in the PQIS 2013 Annual Report.

- The PQIS 2013 Annual Report provided the necessary distillation information to calculate CI information for Jet A, JP-8 and Jet A-1, by PADDs for CONUS and OCONUS regions. Therefore, CI values were calculated using both ASTM D4737 and ASTM D976. This calculation from distillation data was necessary since CI values were missing and were not reported as a value in the database at several instances. In certain instances, where CI information was provided, the method used to obtain that CI value was not given. Due to these reasons, calculations from distillation data were necessary. It should be noted that there were no CN or DCN data available, for all three fuels in the PQIS report.

- The second limitation in the PQIS database was the absence of density, distillation data, and region, from which samples were taken, in several instances. As a result, CI values were not computed and those data points were excluded as bad data, in addition to data points where the PADD location, designating the origin of the samples, was missing.

- For Jet A and Jet A-1 fuels, the volume of fuel was missing for more than 50% of the population even though it contained all the other relevant information for obtaining CI values. Therefore, weighted CI values could not be obtained for Jet A and Jet A-1 fuels, since the results are biased and incomparable to non-weighted CI values.

Thus, non-weighted CI values were calculated for Jet A, Jet A-1, and JP-8; and weighted CI values were calculated for JP-8 fuel. The non-weighted CI values from the PQIS Database for Jet A, Jet A-1 and JP-8 are provided in Table 1, Table 2, and Table 3, respectively while Table 4 shows the weighted JP-8 data, wherein both the non-weighted and weighted CI values are listed by PADD regions and for years 2010 to 2013. The number of data points indicates the actual number of fuel samples that have both density and distillation data to calculate Cetane Index values.

Table 1. Summary of Non-weighted PQIS Jet A Data from 2010 to 2013

2010									
PADD Region	**Data Points**	**CI (D4737-10)**				**CI (D976-06 (2011))**			
		Avg	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
5	17	41.45	0.39	40.66	41.89	39.69	0.53	38.7	40.27
1 to 4 and 6 to 12	U/A*	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
2011									
PADD Region	**Data Points**	**CI (D4737-10)**				**CI (D976-06 (2011))**			
		Avg	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
1	8	45.73	0.77	44.63	46.36	44.53	0.51	43.81	45.01
5	92	41.14	0.4	40.16	42.16	39.25	0.59	37.82	40.23
2 to 4 and 6 to 12	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
2012									
PADD Region	**Data Points**	**CI (D4737-10)**				**CI (D976-06 (2011))**			
		Avg	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
1	8	46.56	0.31	46.06	47.09	45.37	0.31	44.85	45.87
2	2	43.89	N/A	N/A	N/A	42.57	N/A	N/A	N/A
3	21	43.77	1.49	42.37	49.9	42.71	1.11	41.46	47.16
4	9	42.15	0.74	40.94	43.67	39.41	0.82	38.27	41.19
5	24	41.08	0.35	40.22	41.58	39.03	0.44	37.88	39.6
6 to 12	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
2013									
PADD Region	**Data Points**	**CI (D4737-10)**				**CI (D976-06 (2011))**			
		Avg	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
1	18	47.46	0.64	46.33	48.83	46.16	0.56	45.24	47.1
2	1	47.07	N/A	N/A	N/A	45.75	N/A	N/A	N/A
3	84	44.74	2.54	41.82	53.02	43.65	1.93	41.07	50.07
4	39	44.47	1.67	41.27	47.07	42.59	2.29	38.31	45.98
5	12	43.13	0.78	41.91	43.96	41.7	0.98	39.88	43.01
6 and 8 to 12	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
7	1	43.33	N/A	N/A	N/A	41.1	N/A	N/A	N/A

*U/A – Unavailable in PQIS Database; N/A – Not applicable due to single data point

Table 2. Summary of Non-weighted PQIS Jet A-1 Data from 2010 to 2013

2009									
PADD Region	**Data Points**	**CI (D4737-10)**				**CI (D976-06 (2011))**			
		Avg	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
7	3	47.27	0.49	46.79	47.76	44.63	0.52	44.1	45.14
Remaining	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
2010									
PADD Region	**Data Points**	**CI (D4737-10)**				**CI (D976-06 (2011))**			
		Avg	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
1 to 5	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
6	10	48.06	0.38	47.56	48.64	45.79	0.42	45.22	46.34
7	66	45.55	2.42	37.66	56.99	43.28	2.88	32.33	56.56
8	17	45.55	2.01	42.06	49.8	43.75	2.11	40.1	47.97
2011									
PADD Region	**Data Points**	**CI (D4737-10)**				**CI (D976-06 (2011))**			
		Avg	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
1 to 5	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
6	39	46.91	1.17	45.11	49.01	44.19	1.53	41.59	46.5
7	216	45.23	1.88	37.22	48.25	43.34	2.1	35	46.38
8	1	43.16	N/A	N/A	N/A	41.56	N/A	N/A	N/A
2012									
PADD Region	**Data Points**	**CI (D4737-10)**				**CI (D976-06 (2011))**			
		Avg	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
1 to 5	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
6	15	46.7	0.78	45.46	47.84	43.82	1.33	41.89	45.74
7	156	44.67	1.75	37.79	48.74	42.65	2	29.91	46.2
8	5	45.14	0.79	44.21	46.32	42.46	1.18	40.95	44.06
2013									
PADD Region	**Data Points**	**CI (D4737-10)**				**CI (D976-06 (2011))**			
		Avg	**SD**	**Min**	**Max**	**Avg**	**SD**	**Min**	**Max**
1 to 5	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
6	15	47.21	1.55	45.22	52.08	44.75	1.73	42.37	49.52
7	89	45.14	2.03	38.68	48.58	43.07	2.23	35.2	46.49
8	3	47.63	0.62	46.92	48.07	45.03	0.6	44.35	45.47

U/A – Unavailable in PQIS Database; N/A – Not applicable due to single data point

Table 3. Summary of Non-weighted PQIS JP-8 Data from 2010 to 2013

PADD Region	Data Points	CI (D4737-10) Avg	SD	Min	Max	CI (D976-06 (2011)) Avg	SD	Min	Max
2010									
1	2	46.23	0.66	45.76	46.69	43.98	0.83	43.39	44.56
2	224	46.19	1.35	39.82	48.41	45.15	1.53	37.71	47.84
3	406	46.1	2.66	37.47	51.94	46.1	2.66	37.47	51.94
4	27	41.98	0.98	39.51	43.23	39.11	1.29	36	41.01
5	86	40.66	3.11	30.5	46.02	39.34	3.19	29.52	44.87
6	78	46.23	0.44	45.07	47.26	43.02	0.57	41.45	44.27
7	31	46.42	1.24	43.39	48.75	43.86	1.48	40.37	46.6
8	170	42.6	2.56	37.45	48.11	40.64	2.49	35.7	45.8
2011									
1	9	47.05	0.5	45.97	47.78	44.59	0.55	43.73	45.5
2	249	46.14	1.67	40.99	59	45.16	1.9	39.16	59.11
3	445	44.96	3.62	35.78	55.61	43.4	3.49	34.36	53.41
4	16	41.94	0.87	40.85	43.49	38.89	1.17	37.24	40.94
5	104	38.73	2.79	31.59	44.62	37.31	2.72	30.13	43.97
6	89	45.76	0.56	42.2	47.16	42.35	0.7	38.71	44.23
7	55	44.98	2.35	39.53	48.84	42.18	2.58	35.57	46.37
8	158	42.1	2.51	38.07	52.95	40.08	2.43	35.08	50.38
2012									
1	8	47.07	1.54	43.39	48.08	44.66	1.43	41.28	45.7
2	229	46.39	1.4	43.54	60.65	45.24	1.69	41.18	60.03
3	400	45.89	2.45	38.85	51.99	44.27	2.25	37.75	49.78
4	46	43.37	1.33	41.62	48.13	41.04	1.99	38.38	46.83
5	58	37.61	1.95	32.18	43.12	36.2	2.07	30.32	42.67
6	75	46.49	0.63	45.07	47.61	43.25	0.86	41.2	44.81
7	20	46.33	2.47	41.23	48.66	43.67	2.31	39.13	45.93
8	145	42.65	2.67	39.6	47.81	40.53	2.43	37.59	45.1
2013									
1	7	46.09	1.06	44.12	47.61	43.48	1.07	41.85	45.25
2	263	45.95	2.06	38.31	61.15	44.79	2.75	33.07	60.39
3	217	46.98	1.74	44.03	51.62	45.19	1.68	41.36	48.67
4	23	44.66	1.69	41.91	46.55	43.35	1.72	40.44	45.47
5	50	41.46	2.47	35.66	44.35	40.57	3.25	29.27	44.32
6	141	46.24	0.68	40.17	47.92	42.95	1.00	33.81	45.27
7	8	47.03	2.20	42.21	50.04	44.94	2.06	40.76	48.17
8	106	43.24	3.00	39.78	48.32	41.1	2.80	37.65	46.08

U/A – Unavailable in PQIS Database; N/A – Not applicable due to single data point

Table 4. Summary of Weighted PQIS JP-8 Data from 2010 to 2013

PADD Region	Data Points	CI (D4737-10) Avg	CI (D4737-10) SD	CI (D4737-10) Min	CI (D4737-10) Max	CI (D976-06 (2011)) Avg	CI (D976-06 (2011)) SD	CI (D976-06 (2011)) Min	CI (D976-06 (2011)) Max
2010									
1	2	45.96	0.54	45.76	46.69	43.65	0.68	43.39	44.56
2	224	46.43	1.28	39.82	48.41	45.34	1.43	37.71	47.84
3	406	46.06	2.59	37.47	51.94	44.42	2.65	35.92	50.83
4	27	41.74	1.15	39.51	43.23	38.77	1.49	36.00	41.01
5	86	39.80	4.34	30.50	46.02	38.74	4.54	29.52	44.87
6	78	46.26	0.42	45.07	47.26	43.06	0.56	41.45	44.27
7	31	46.73	1.28	43.39	48.75	44.25	1.55	40.37	46.60
8	170	44.46	2.70	37.45	48.11	42.53	2.57	35.70	45.80
2011									
1	9	47.03	0.52	45.97	47.78	44.52	0.57	43.73	45.50
2	249	46.14	1.31	40.99	59.00	45.14	1.48	39.16	59.11
3	445	45.65	3.34	35.78	55.61	44.09	3.36	34.36	53.41
4	16	41.93	0.87	40.85	43.49	38.85	1.17	37.24	40.94
5	104	39.69	3.43	31.59	44.62	38.18	3.26	30.13	43.97
6	89	45.66	0.84	42.20	47.16	42.26	0.95	38.71	44.23
7	55	44.85	2.44	39.53	48.84	42.08	2.73	35.57	46.37
8	158	43.28	2.63	38.07	52.95	41.22	2.63	35.08	50.38
2012									
1	8	47.38	1.17	43.39	48.08	44.94	1.09	41.28	45.70
2	229	46.22	1.10	43.54	60.65	44.99	1.46	41.18	60.03
3	400	46.17	2.37	38.85	51.99	44.56	2.38	37.75	49.78
4	46	43.46	1.30	41.62	48.13	41.19	1.97	38.38	46.83
5	58	38.36	2.68	32.18	43.12	37.03	2.89	30.32	42.67
6	75	46.44	0.70	45.07	47.61	43.18	0.98	41.20	44.81
7	20	46.44	2.28	41.23	48.66	43.74	2.21	39.13	45.93
8	145	44.41	0.39	39.60	47.81	42.15	0.35	37.59	45.10
2013									
1	7	46.51	1.01	44.12	47.61	43.95	1.13	41.85	45.25
2	263	45.35	2.19	38.31	61.15	43.90	3.03	33.07	60.39
3	217	47.21	1.63	44.03	51.62	45.57	1.59	41.36	48.67
4	23	45.01	1.55	41.91	46.55	43.71	1.59	40.44	45.47
5	50	40.54	3.14	35.66	44.35	39.13	3.29	29.27	44.32
6	141	46.25	0.70	40.17	47.92	42.96	1.04	33.81	45.27
7	8	47.47	2.32	42.21	50.04	45.38	2.25	40.76	48.17
8	106	45.80	0.31	39.78	48.32	43.43	0.29	37.65	46.08

2.2 REVIEW OF CRC REPORT

The data from Coordinating Research Council (CRC) Aviation Committee report, "*World Fuel Sampling Program, CRC Report No. 647*" is presented in Table 5 [2]. The original data from the report only contained distillation and density information from which CI values were computed and categorized by PADDs along with relevant statistics. It should be noted that no CN or DCN information was available in the report. Also, the number of data points are so low compared to PQIS database, that statistical plots of the same are insignificant for this data set [2]. Alternatively, the data set will be used to study the properties of maximum ATJ blends.

Table 5. World Survey of Fuels containing Non-weighted CI values from CRC Report

Jet A									
PADD Region	CI (D4737-10)					CI (D976-06)			
	Data Points	Avg	SD	Min	Max	Avg	SD	Min	Max
1	2	46.09	1.56	44.98	47.19	44.94	2.62	43.09	46.8
2	5	45.77	0.85	45.05	46.95	44.65	1.07	43.66	45.97
3	1	47.33	N/A	N/A	N/A	46.79	N/A	N/A	N/A
4	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
5	4	44.41	5.3	36.95	49.19	43.42	6.07	35.3	49.72
11 (Canada)	1	45.67	N/A	N/A	N/A	43.76	N/A	N/A	N/A
JP-8									
PADD Region	CI (D4737-10)					CI (D976-06)			
	Data Points	Avg	SD	Min	Max	Avg	SD	Min	Max
1	5	47.32	1.04	46.29	48.89	45.46	1.07	44.39	46.94
2	3	45.32	4.22	40.72	49.01	43.34	4.45	38.34	46.84
3	1	40.78	N/A	N/A	N/A	39.88	N/A	N/A	N/A
4	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
5	1	47.38	N/A	N/A	N/A	46	N/A	N/A	N/A
JP-5									
PADD Region	CI (D4737-10)					CI (D976-06)			
	Data Points	Avg	SD	Min	Max	Avg	SD	Min	Max
5	1	42.74	N/A	N/A	N/A	43.11	N/A	N/A	N/A
8	1	41.86	N/A	N/A	N/A	41.06	N/A	N/A	N/A
Jet A-1									
PADD Region	CI (D4737-10)					CI (D976-06)			
	Data Points	Avg	SD	Min	Max	Avg	SD	Min	Max
6	1	47.71	N/A	N/A	N/A	45.2	N/A	N/A	N/A
7	13	44	2.1	40.77	47.6	41.63	2.34	37.72	45.89
8[a]	4	46.39	0.94	45.09	47.17	43.74	0.76	42.69	44.41
8[b]	1	47.23	N/A	N/A	N/A	45.105	N/A	N/A	N/A
8[c]	1	40.34	N/A	N/A	N/A	37.36	N/A	N/A	N/A
8[d]	1	40.91	N/A	N/A	N/A	38.05	N/A	N/A	N/A
9	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A	U/A
10	2	42.98	3.08	40.81	45.16	40.95	1.76	39.71	42.19
11	6	41.39	2.59	37.48	43.95	39.73	3.25	35.32	43.31
12 (Part Syn.)	1	49.84	N/A	N/A	N/A	46.92	N/A	N/A	N/A
12 (100% Syn.)	1	57.79	N/A	N/A	N/A	53.48	N/A	N/A	N/A

[a] - Conventional petroleum based jet fuel; [b] - Oil Shale, Australia (% Nitrogen content unknown)
[c] - Oil Shale, Australia (Low Nitrogen); [d] - Oil Shale, Australia (High Nitrogen)
U/A – Unavailable in PQIS Database; N/A – Not applicable due to single data point

2.3 REVIEW OF TRI-SERVICES DATA

All cetane property data from the report "*Tri-service Jet Fuel Characterizations for DOD Applications – Fit-For-Purpose and Trace Impurity Evaluations*", are presented in Table 6 [3]. It should be noted that this study was conducted with one sample from each CONUS PADD and therefore, statistical analysis cannot be performed on the data set. However, the data will be used for predicting cetane properties of maximum ATJ blends, for Jet A and JP-8 fuels.

Table 6. Non-weighted Tri-Services Data (2014)

Sample No. on Report	Sample Name	CI (D4737-10)	CI (D976-06)	CN (D613)	DCN (D6890)
1	ATJ	61.08	54.47	<19.4	15.2
2	ATJ/JP-8 (50/50)	52.18	48.36	30.8	34.6
7	JP-8 Blend Stock	47.97	46.54	46	45.4
8	JP-8 - PADD 1	47.74	46.23	45.4	45.7
9	JP-8 - PADD 2	47.14	46.38	47.4	49.7
10	JP-8 - PADD 3	49.27	47.52	46.1	45.9
11	JP-8 - PADD 4	44.33	43.15	43	42.3
12	JP-8 - PADD 5	44.68	42.74	43	46.4
25	JP-8 - WPAFB	47.75	46.02	47.4	47.9
13	Jet A - FAME Sensitive	42.34	39.79	41.3	41
14	Jet A - PADD 1	49.39	48.48	48.5	45.7
15	Jet A - PADD 2	41.48	40.37	39.4	39.9
16	Jet A - PADD 3	52.68	50.5	49.3	50.1
17	Jet A - PADD 4	44.51	41.6	44	44.9
18	Jet A - PADD 5	48.1	47.12	43.5	43.8
22	Jet A - Nominal	46.92	45.43	47	48.3
23	Jet A - Best Case	51.58	48.29	47.9	48.8

3.0 ANALYSIS OF PQIS LITERATURE DATA

The statistical CI values generated from the PQIS database are shown from Figure 4 to Figure 11. It should be noted that CRC and Tri-Services literature data had an insignificant number of data points and therefore statistical plots were not generated. The general trend for Jet A fuel CONUS region is that the CI value decreases from PADD region 1 to region 5, while for Jet A-1 in the OCONUS region there is significant overlap in the range and the variation in CI values in those OCONUS regions; those regions were concluded to be statistically insignificant. There is no clear trend in JP-8 CI values. It should be noted that CI values were computed using both D976 and D4737 methods. The CI values of maximum ATJ blends will be predicted for both methods as well.

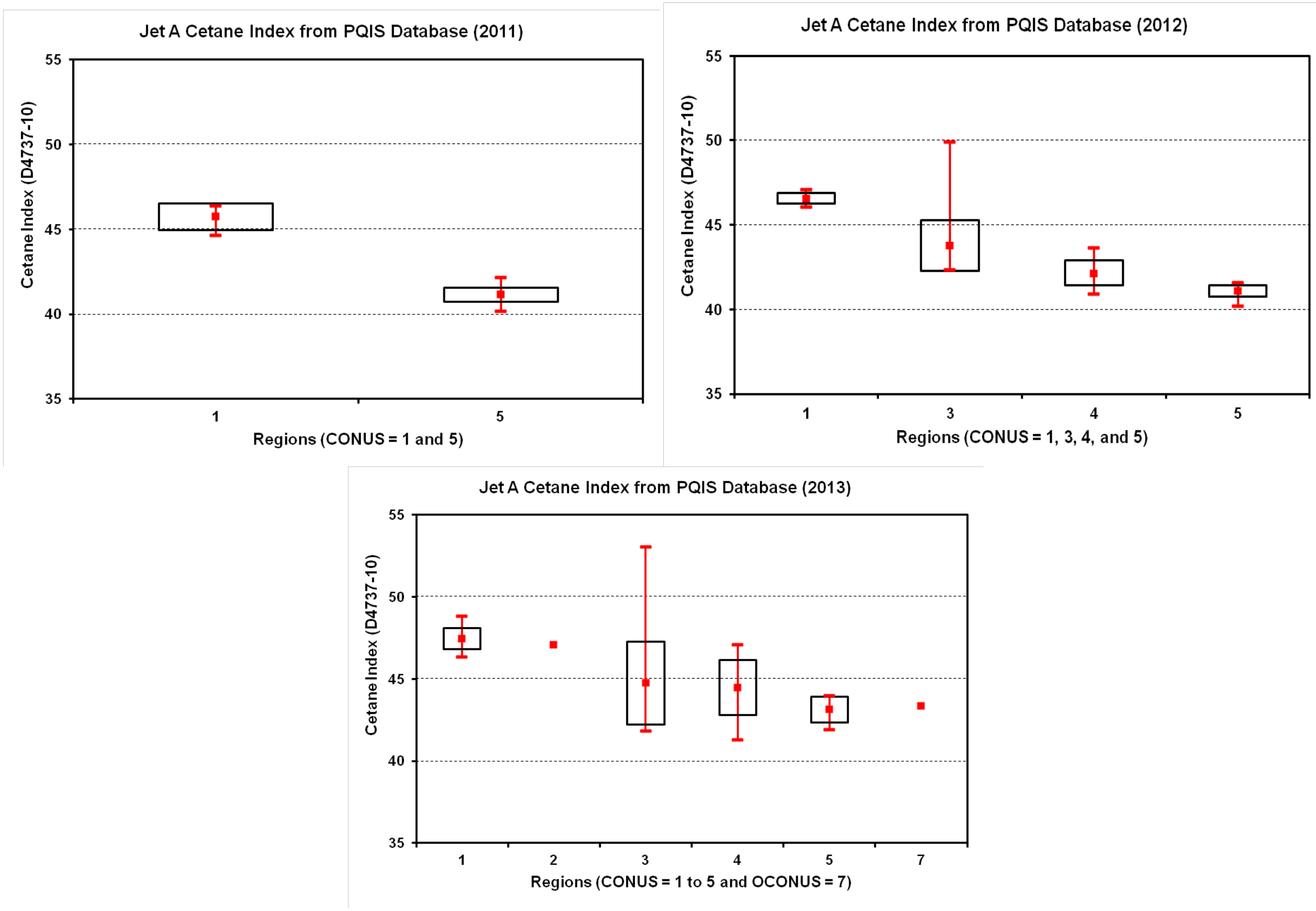

Figure 4. Non-weighted Cetane Index (D4737-10) of Jet A from PQIS Database for 2011, 2012 and 2013

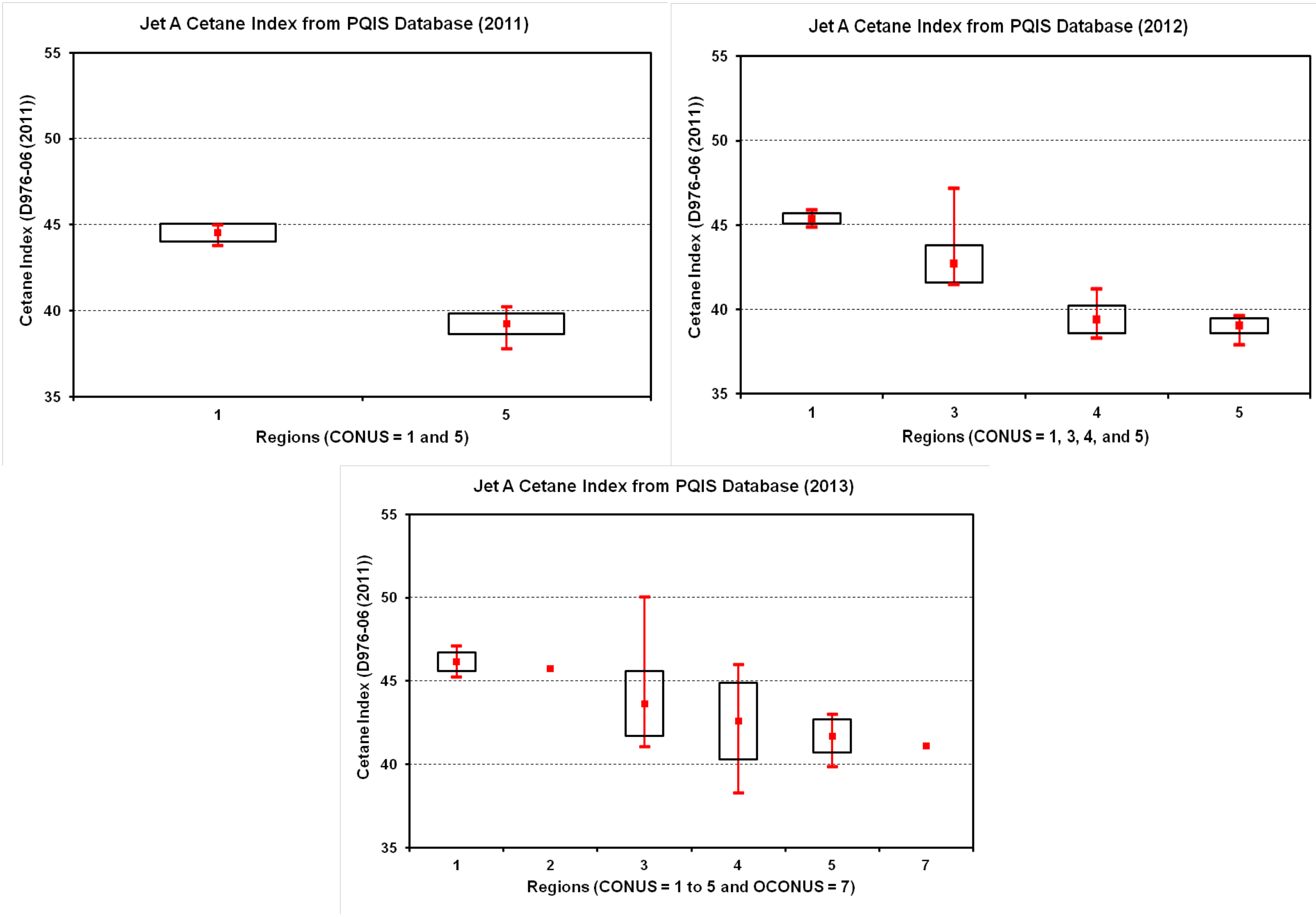

Figure 5. Non-weighted Cetane Index (D976-06 (2011)) of Jet A from PQIS Database for 2011, 2012 and 2013

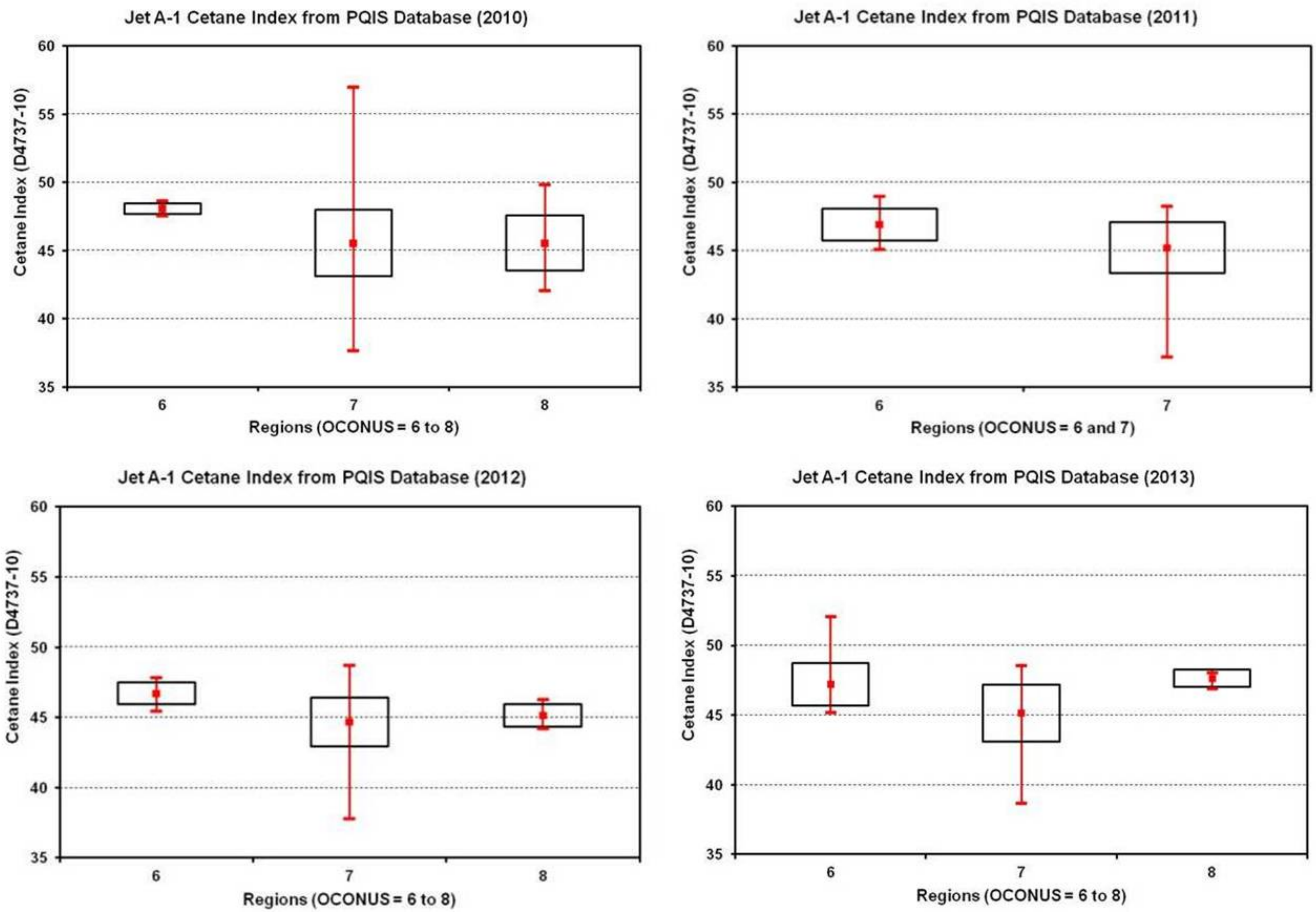

Figure 6. Non-weighted Cetane Index (D4737-10) of Jet A-1 from PQIS Database from 2010 to 2013

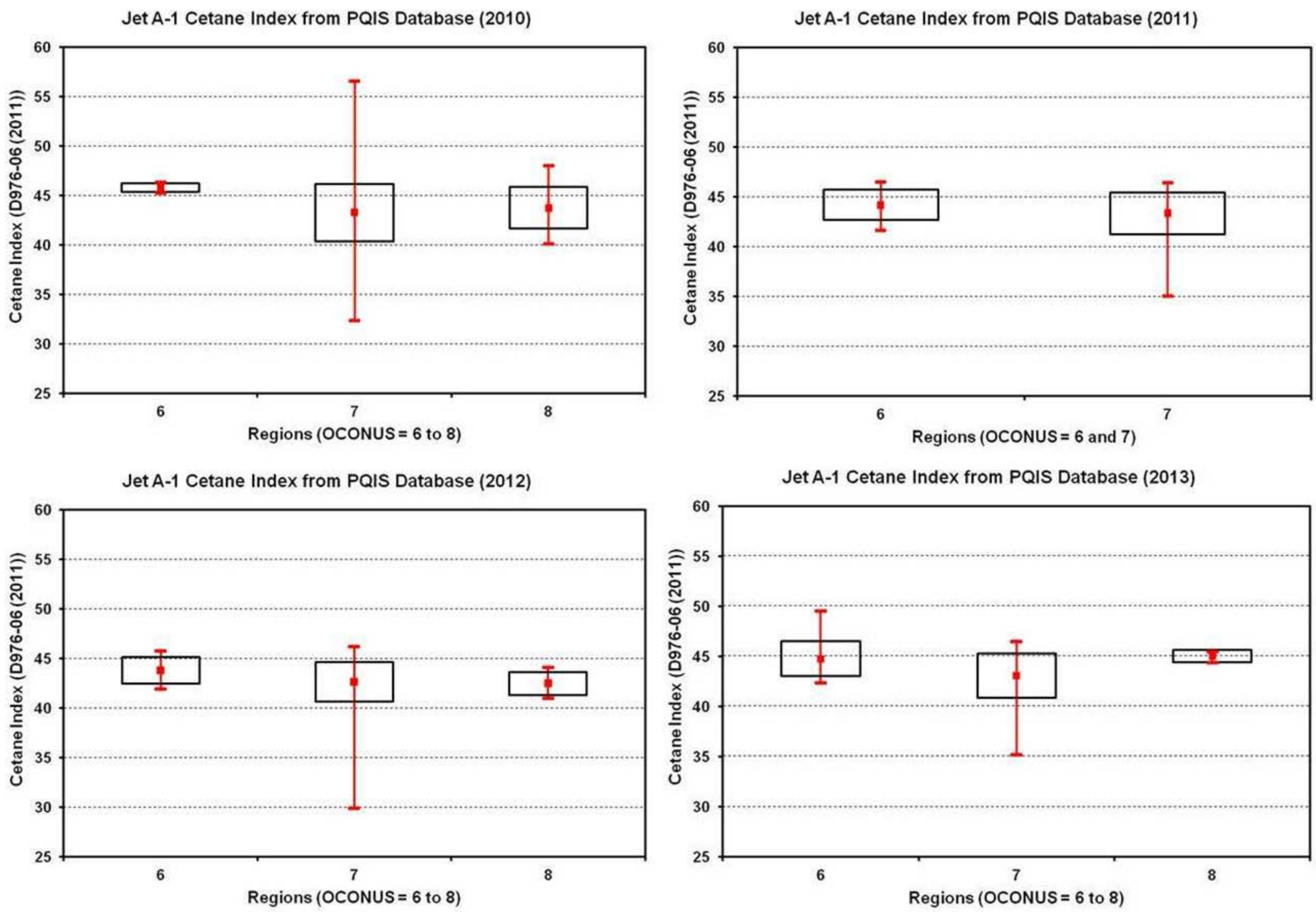

Figure 7. Non-weighted Cetane Index (D976-06 (2011)) of Jet A-1 from PQIS Database from 2010 to 2013

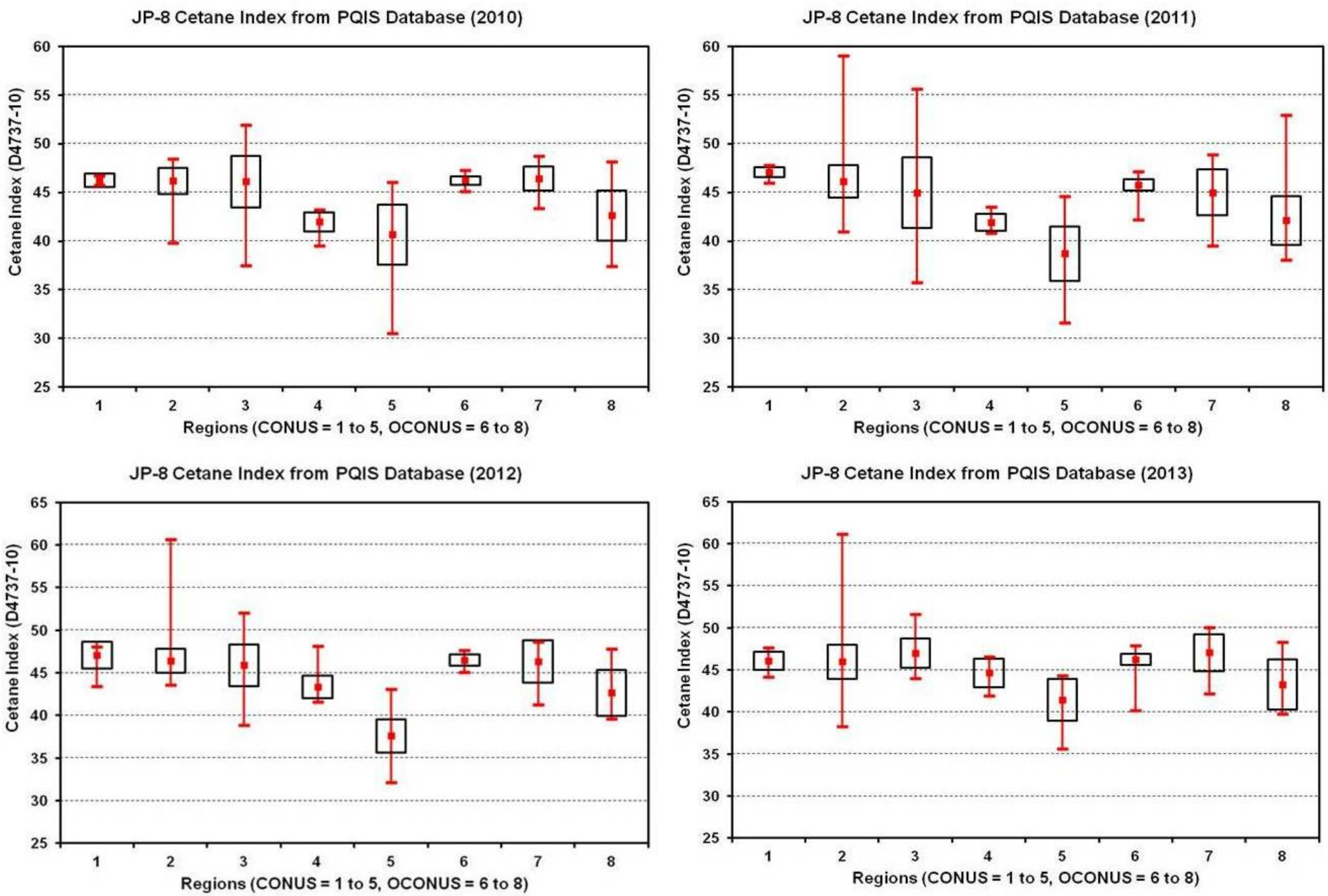

Figure 8. Non-weighted Cetane Index (D4737-10) of JP-8 from PQIS Database from 2010 to 2013

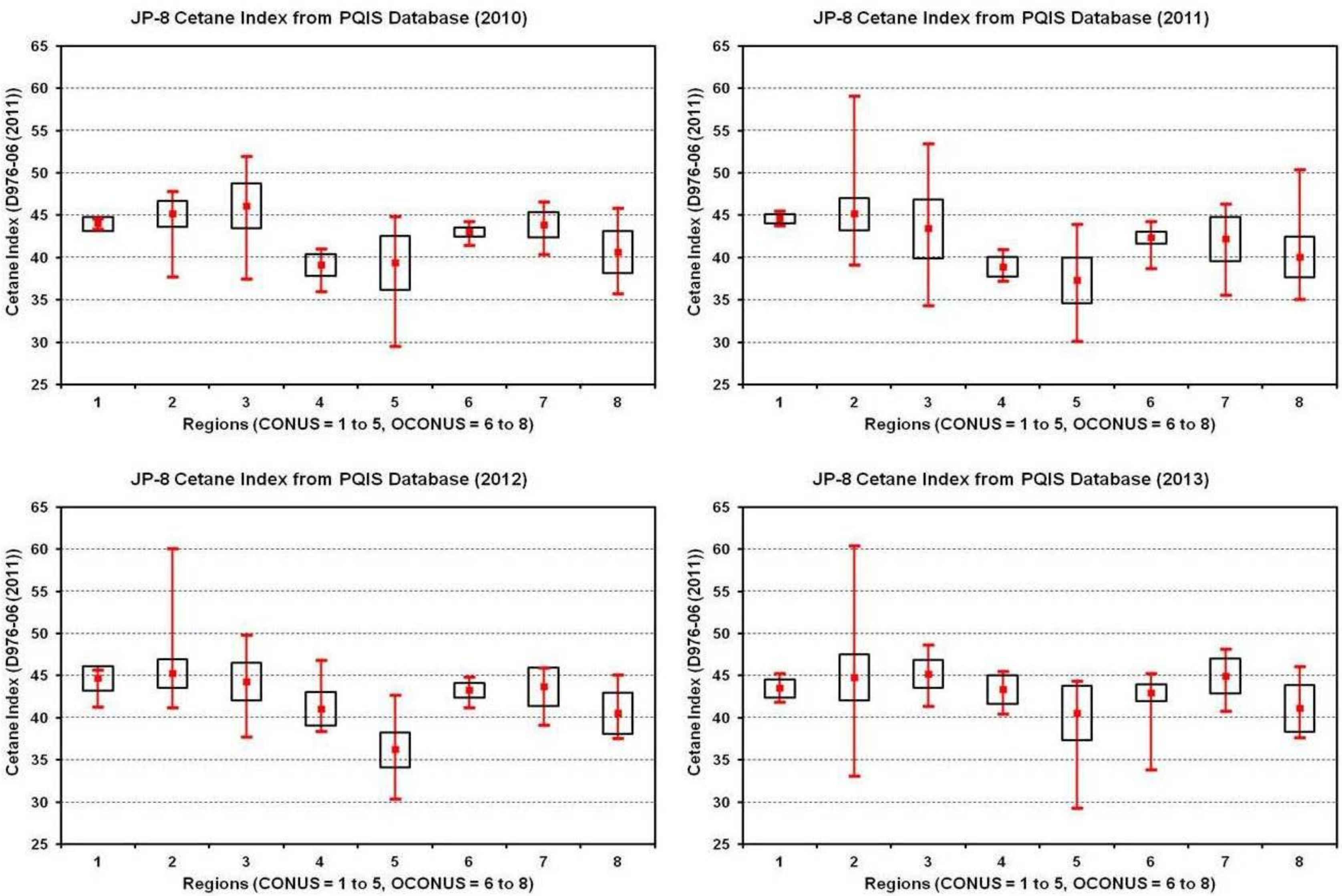

Figure 9. Non-weighted Cetane Index (D976-06 (2011)) of JP-8 from PQIS Database from 2010 to 2013

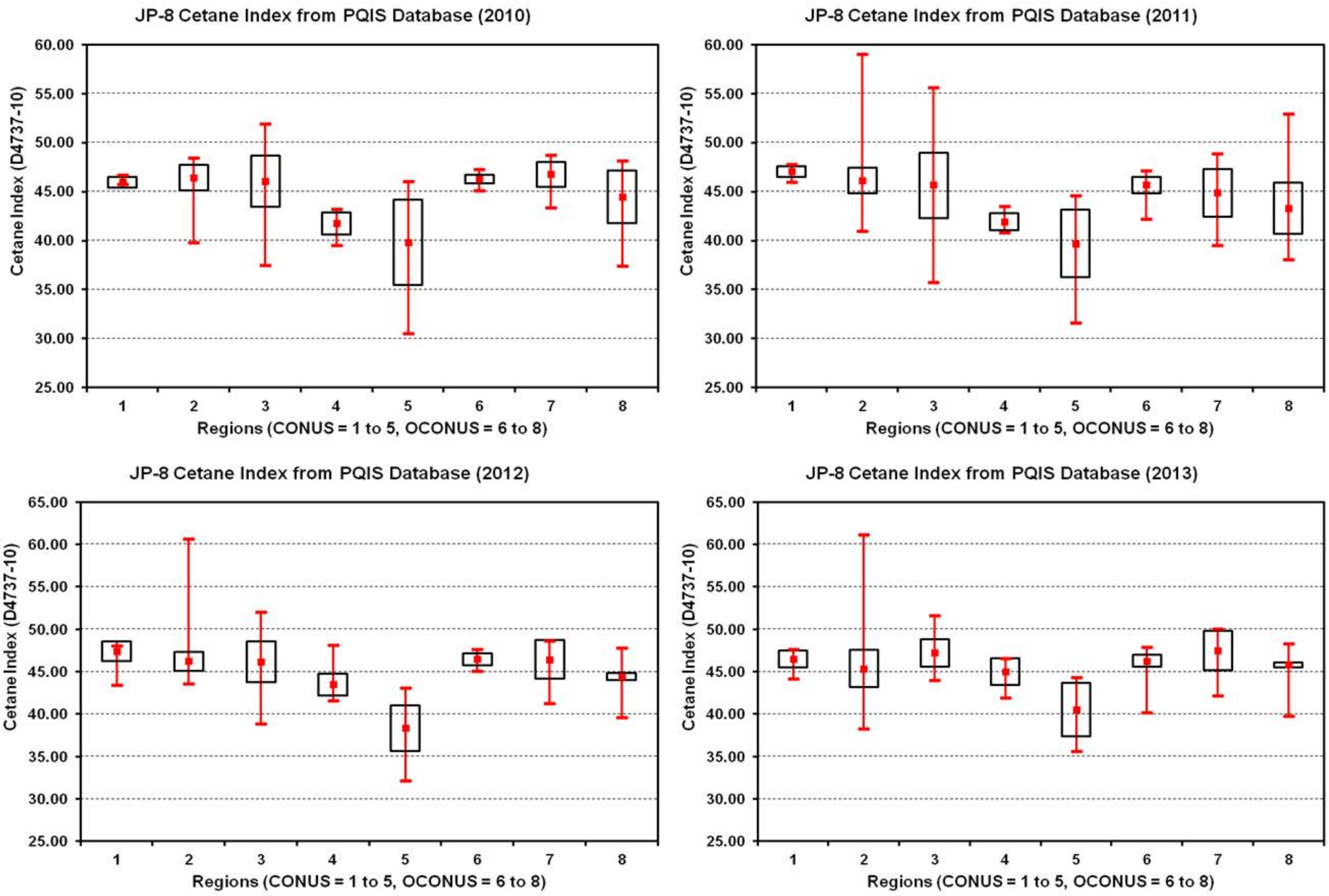

Figure 10. Weighted Cetane Index (D4737-10) of JP-8 from PQIS Database from 2010 to 2013

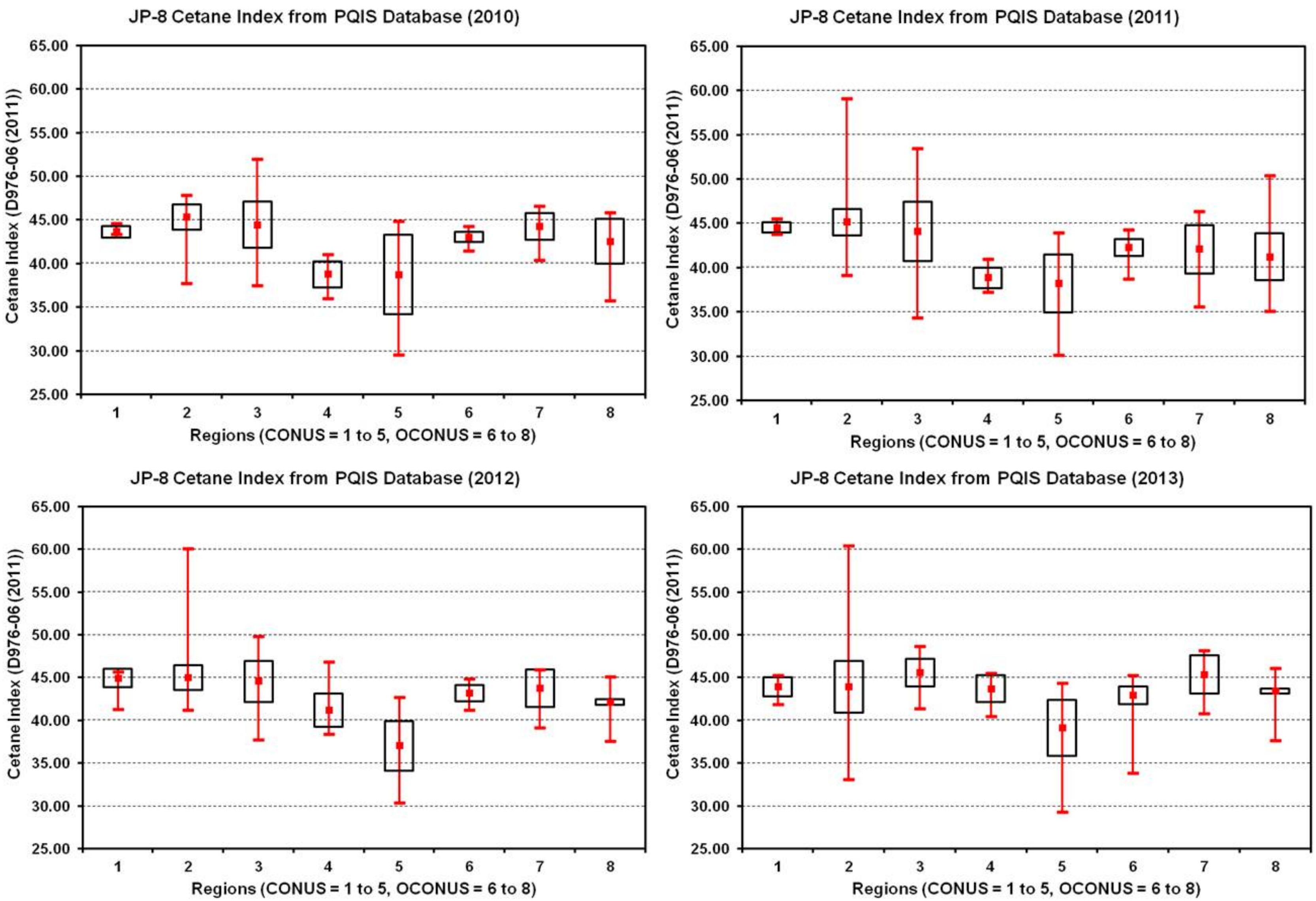

Figure 11. Weighted Cetane Index (D976-06 (2011)) of JP-8 from PQIS Database from 2010 to 2013

4.0 DEVELOPING DATA CORRELATIONS

The summary of cetane property results for ATJ-JP-8 blends from Task 2.4 of WD0024 is listed in Table 7.

Table 7. Calculated CI Data for JP-8 as Published in 2013 PQIS 2013 Annual Report

% ATJ	Density (15°C)	CI (D4737-10)	CI (D976-06 (2011))	DCN (D6890)	CN (D613)
100	0.7575	60.30	53.90	15.65	<19.4
85	0.7635	58.10	52.53	24.50	<19.4
65	0.7710	56.14	51.41	31.89	26.70
50	0.7766	55.04	50.97	37.04	32.00
35	0.7820	53.77	50.28	41.02	36.40
25	0.7857	53.30	50.22	42.66	41.00
15	0.7896	52.50	49.83	45.15	44.20
0	0.7951	51.18	49.14	47.68	46.90

A plot of the CI data obtained using four variable method ASTM D4737-10 and D976-06 (2011) versus percent ATJ in JP-8–ATJ blend is shown in Figure 12. A plot of DCN versus percent ATJ in JP-8–ATJ blend is shown in Figure 13 along with the regression equation that describes the data with the best fit.

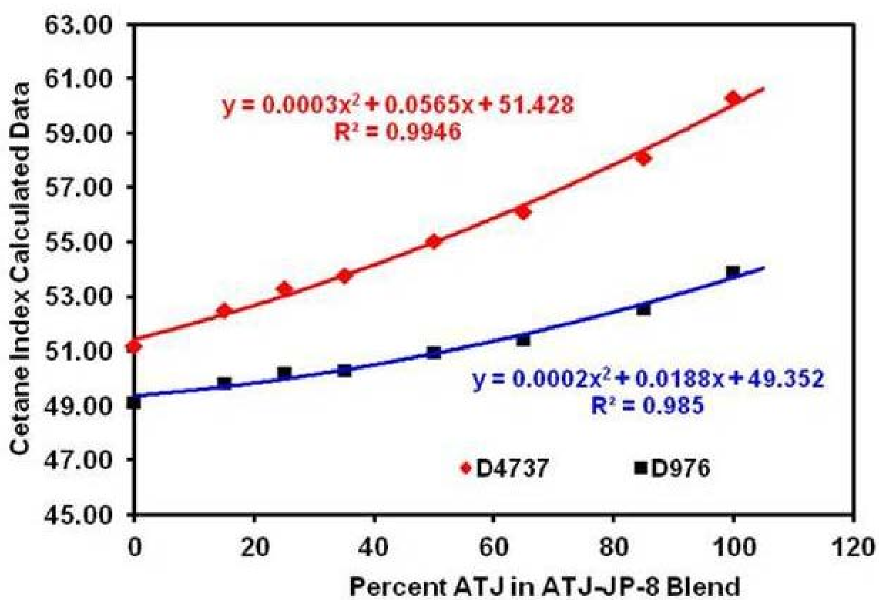

Figure 12. Cetane Index Variation in JP-8–ATJ Fuel Blend

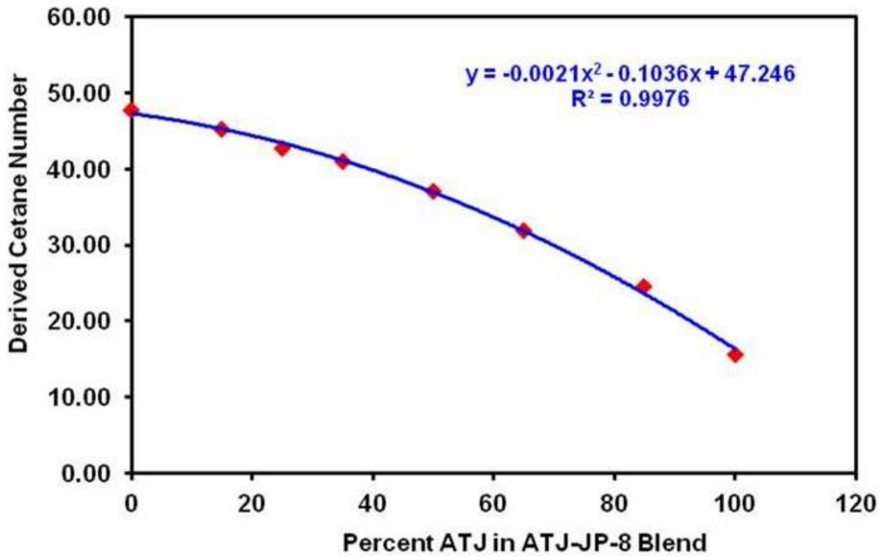

Figure 13. Derived Cetane Number Variation in JP-8–ATJ Fuel Blend

The decreasing DCN trend in Figure 13 is what is expected when synthetic jet fuels are blended with petroleum based jet fuels. However, Figure 12 is contrary to the trend, indicating the CI correlation equations stated in ASTM D4737-10 and ASTM D976-06 (2011) are not a direct measure of combustion quality of jet fuels. Cetane Number (D613) versus percent ATJ in JP-8–ATJ blend is shown in Figure 14.

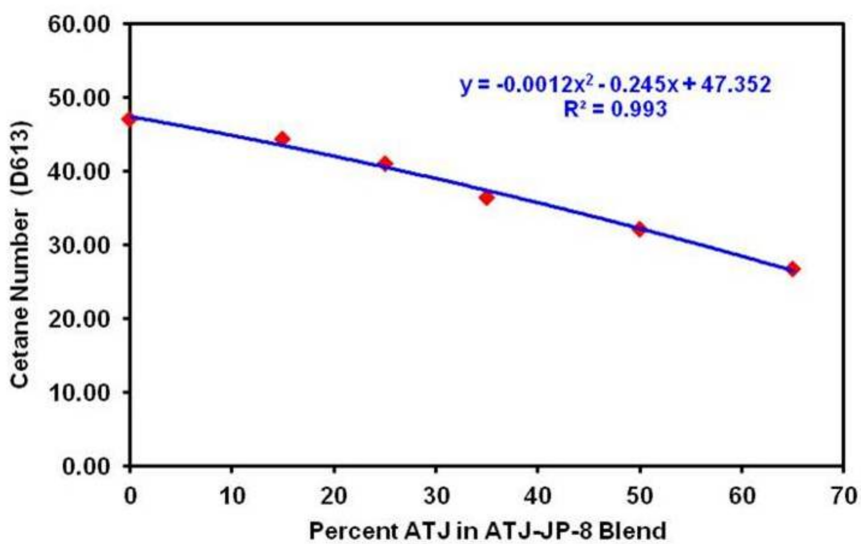

Figure 14. Cetane Number Variation in JP-8-ATJ Fuel Blend

The correlation equations were differentiated with respect to volume percentage of ATJ in the fuel blend to yield the equations required for numerical computation of cetane properties for maximum ATJ blends. If 'i' refers to volume percentage of ATJ in the fuel blend, then:

i. $DCN_{(i+1)} = DCN_{(i)} - [(0.0042 \cdot i) + 0.1036]$

ii. $CN_{(i+1)} = CN_{(i)} - [(0.0024 \cdot i) + 0.2450]$

iii. $CI(D4737)_{(i+1)} = CI(D4737)_{(i)} + [(0.0006 \cdot i) + 0.0565]$

iv. $CI(D976)_{(i+1)} = CI(D976)_{(i)} + [(0.0004 \cdot i) + 0.0188]$

The above equations could either be programmed or used in MS Excel, starting with iteration i=0%, corresponding to neat jet fuel, computed up to i=49%, which yields cetane property values at (i+1) or 50%, corresponding to 50/50-ATJ/Jet fuel blends, also called maximum ATJ blends. The subsequent section presents the results obtained by applying the above algorithm to data set that has been reviewed in the literature.

5.0 CETANE PROPERTIES OF ATJ BLENDS

The numerical iterative technique using the above equations were applied to PQIS, CRC and Tri-services data set to obtain cetane properties of maximum ATJ blends.

5.1 MAXIMUM ATJ BLEND CETANE INDEX FOR PQIS DATASET

The CI values of jet fuels versus maximum ATJ blend for PADD regions are presented from Table 8 to Table 11. Non-weighted statistical quantities such as mean, standard deviation, and range were determined for Jet A, Jet A-1, and JP-8 fuels, while the same weighted statistical quantities were determined only for JP-8 fuel because of the availability of sufficient data in PQIS database.

Overall, for all the jet fuels it was determined that the CI value maximum ATJ blend increased by 7% to 9% using the four variable CI D4737 method, while the CI obtained using D976 method showed an overall increase in CI between 3% and 4%. Because of the lack of CN and DCN information in the PQIS report, no statistical projections were made and it is recommended that this information be added to future releases of PQIS database.

Table 8. Non-weighted Cetane Index of Jet A versus 50/50-ATJ/Jet A – PQIS Dataset

PADD Region	CI (D4737-10)			CI (D976-06 (2011))		
	Jet A	50/50 ATJ/Jet A	% Increase	Jet A	50/50 ATJ/Jet A	% Increase
1	47.46	51.05	7.56	46.16	47.61	3.14
2	47.07	50.66	7.63	45.75	47.2	3.17
3	44.74	48.33	8.02	43.65	45.1	3.32
4	44.47	48.06	8.07	42.59	44.04	3.40
5	43.13	46.72	8.32	41.7	43.15	3.48
7	43.33	46.92	8.29	41.1	42.55	3.53

Table 9. Non-weighted Cetane Index of Jet A-1 versus 50/50-ATJ/Jet A-1 – PQIS Dataset

PADD Region	CI (D4737-10)			CI (D976-06 (2011))		
	Jet A-1	50/50 ATJ/Jet A-1	% Increase	Jet A-1	50/50 ATJ/Jet A-1	% Increase
6	47.21	50.8	7.60	44.75	46.2	3.24
7	45.14	48.73	7.95	43.07	44.52	3.37
8	47.63	51.22	7.54	45.03	46.48	3.22

Table 10. Non-weighted Cetane Index of JP-8 versus 50/50-ATJ/JP-8 – PQIS Dataset

PADD Region	CI (D4737-10)			CI (D976-06 (2011))		
	JP-8	50/50 ATJ/JP-8	% Increase	JP-8	50/50 ATJ/JP-8	% Increase
1	46.09	49.68	7.79	43.48	44.93	3.33
2	45.95	49.54	7.81	44.79	46.24	3.24
3	46.98	50.57	7.64	45.19	46.64	3.21
4	44.66	48.25	8.04	43.35	44.8	3.34
5	41.46	45.05	8.66	40.57	42.02	3.57
6	46.24	49.83	7.76	42.95	44.40	3.38
7	47.03	50.62	7.63	44.94	46.39	3.23
8	43.24	46.83	8.30	41.10	42.55	3.53

Table 11. Weighted Cetane Index of JP-8 versus 50/50-ATJ/JP-8 – PQIS Dataset

PADD Region	CI (D4737-10)			CI (D976-06 (2011))		
	JP-8	50/50 ATJ/JP-8	% Increase	JP-8	50/50 ATJ/JP-8	% Increase
1	46.51	50.10	7.72	43.95	45.40	3.30
2	45.35	48.94	7.92	43.90	45.35	3.30
3	47.21	50.80	7.60	45.57	47.02	3.18
4	45.01	48.60	7.98	43.71	45.16	3.32
5	40.54	44.13	8.86	39.13	40.58	3.71
6	46.25	49.84	7.76	42.96	44.41	3.38
7	47.47	51.06	7.56	45.38	46.83	3.20
8	45.80	49.39	7.84	43.43	44.88	3.34

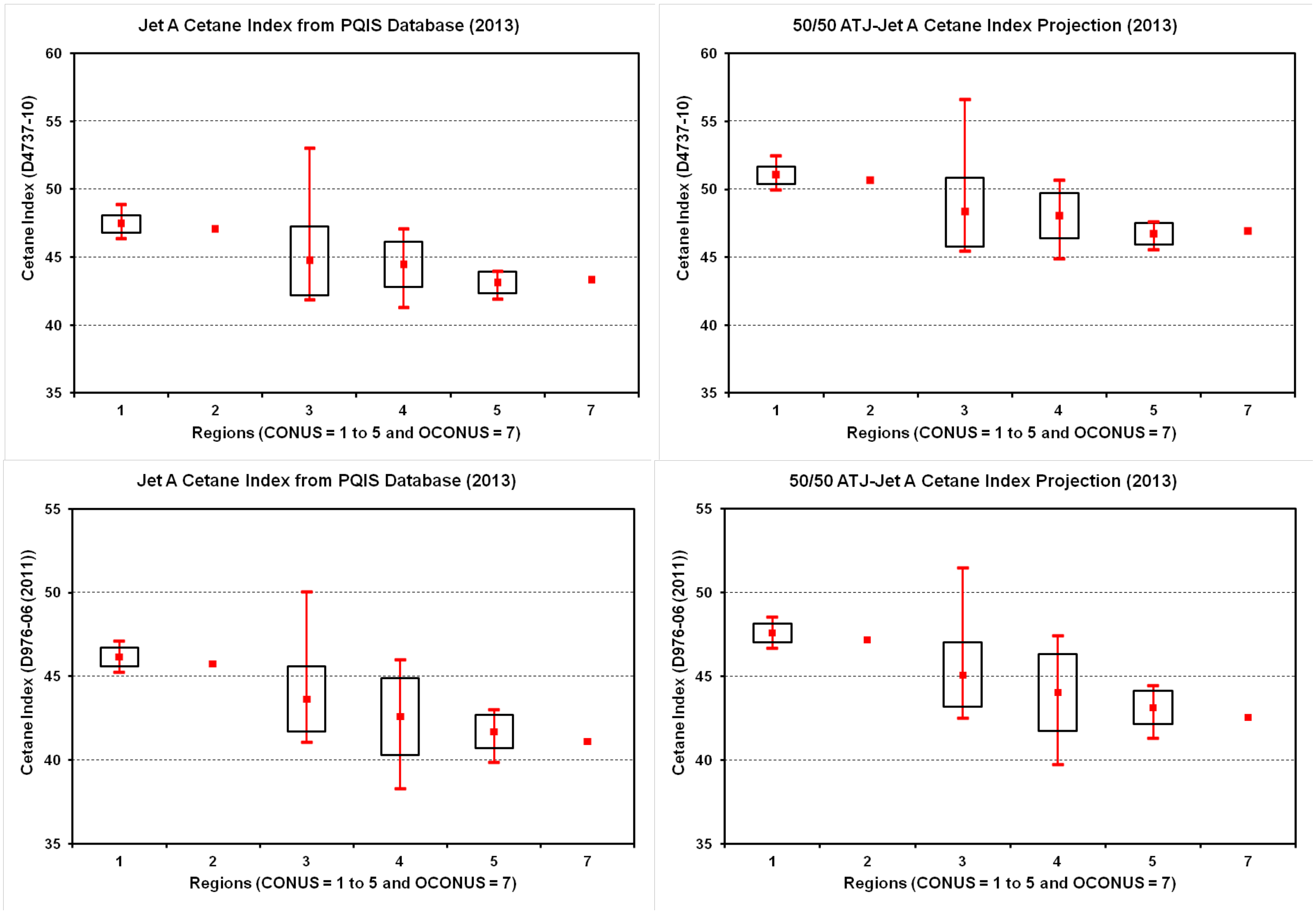

Figure 15. Non-weighted Cetane Index of Jet A versus 50/50-ATJ/Jet A

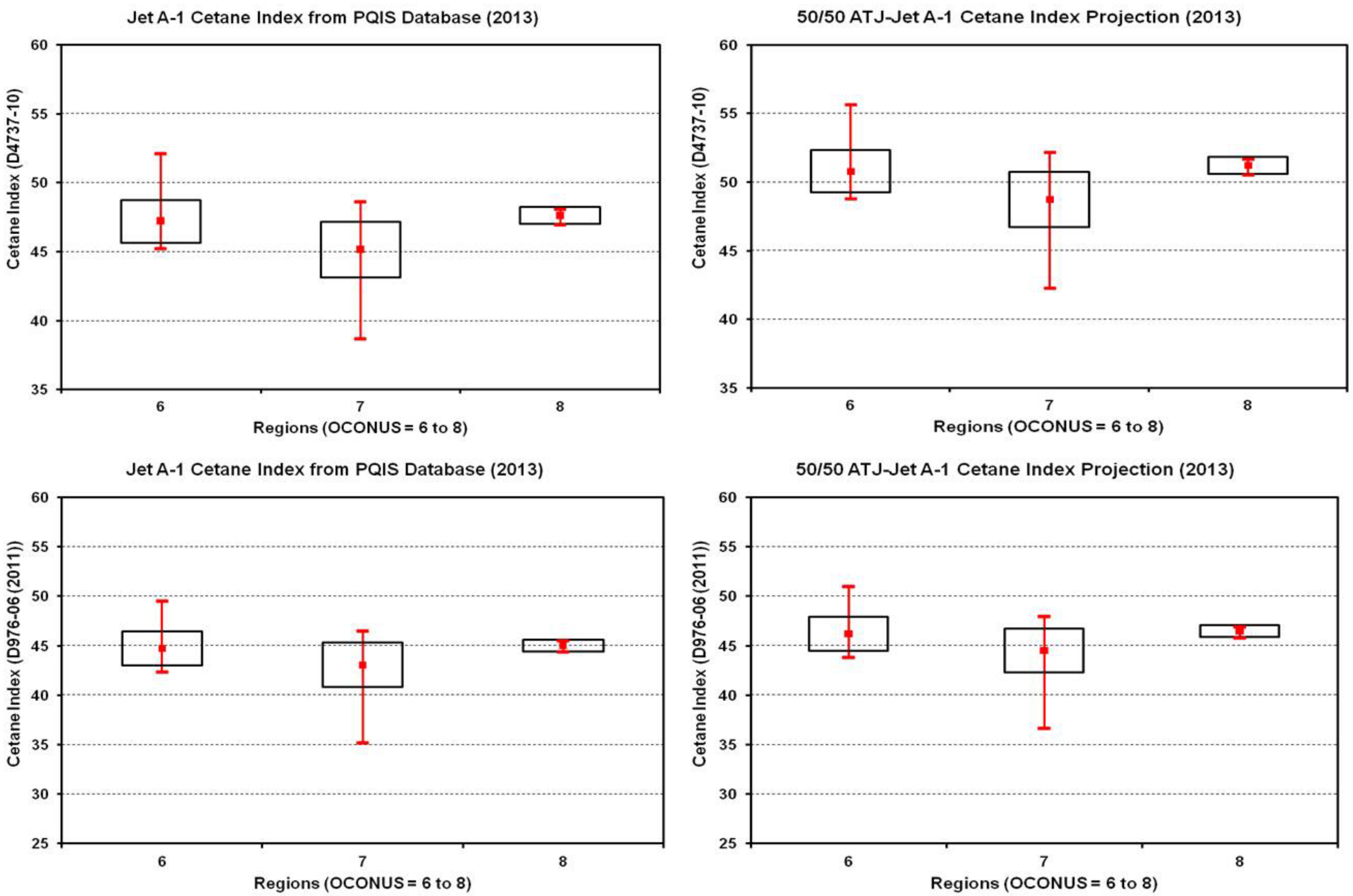

Figure 16. Non-weighted Cetane Index of Jet A-1 versus 50/50-ATJ/Jet A-1

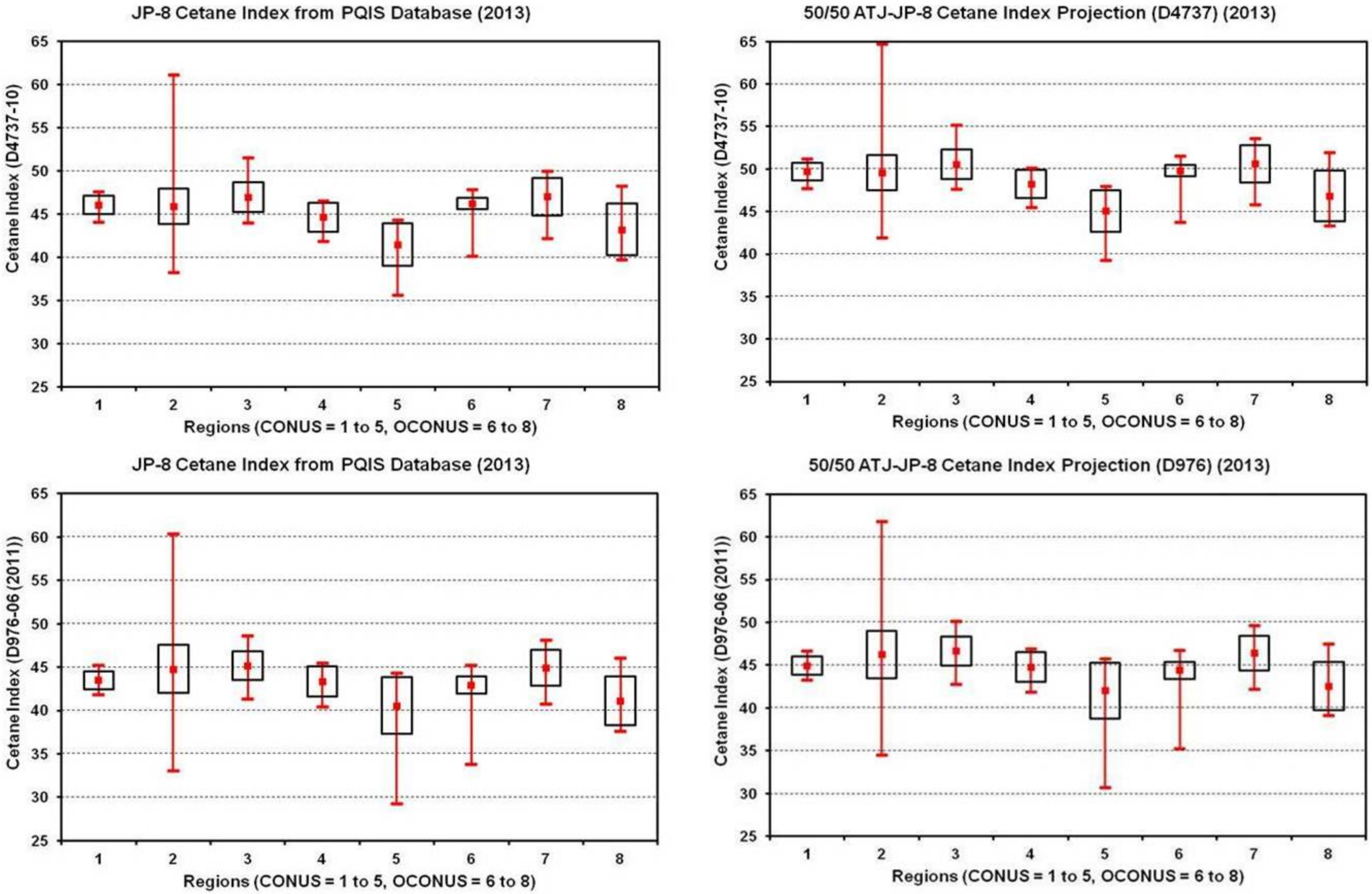

Figure 17. Non-weighted Cetane Index of JP-8 versus 50/50-ATJ/JP-8

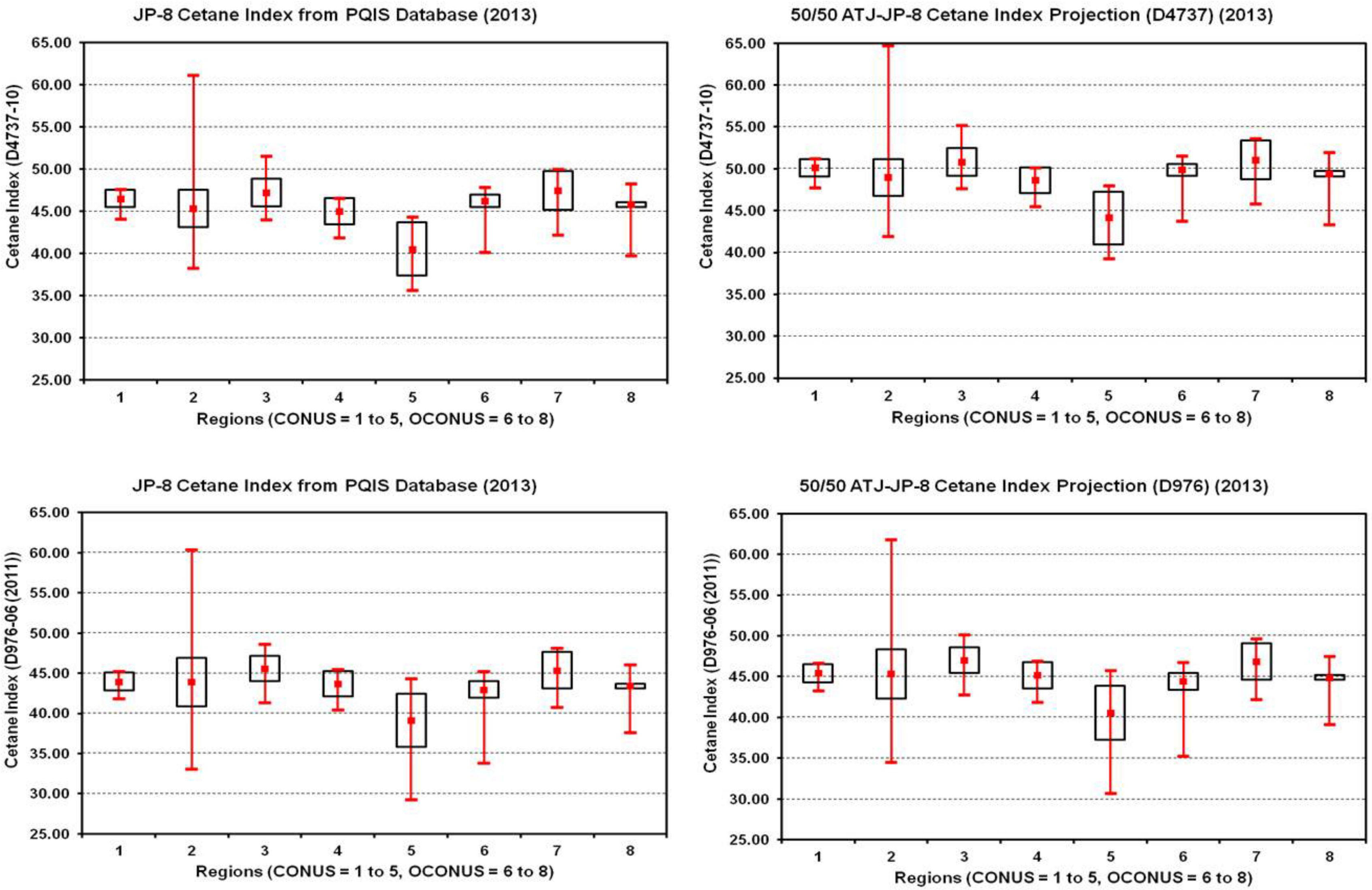

Figure 18. Weighted Cetane Index of JP-8 versus 50/50-ATJ/JP-8

5.2 MAXIMUM ATJ BLEND CETANE INDEX FOR CRC DATASET

The projected CI values of maximum ATJ blends for the CRC data set are shown from Table 12 to Table 14.

Table 12. Non-weighted Cetane Index of Jet A versus 50/50-ATJ/Jet A – CRC Dataset

PADD Region	CI (D4737-10)			CI (D976-16 (2011))		
	Jet A	50/50 ATJ/Jet A	% Increase	Jet A	50/50 ATJ/Jet A	% Increase
1	46.09	49.68	7.79	46.09	47.54	3.15
2	45.77	49.36	7.84	45.77	47.22	3.17
3	47.33	50.92	7.59	47.33	48.78	3.06
4	U/A	U/A	U/A	U/A	U/A	U/A
5	44.41	48	8.08	44.41	45.86	3.27
11 (Canada)	45.67	49.26	7.86	45.67	47.12	3.17

U/A - Unavailable

Table 13. Non-weighted Cetane Index of Jet A-1 versus 50/50-ATJ/Jet A-1 – CRC Dataset

PADD Region	CI (D4737-10)			CI (D976-16 (2011))		
	Jet A-1	50/50 ATJ/Jet A-1	% Increase	Jet A-1	50/50 ATJ/Jet A-1	% Increase
6	47.71	51.3	7.52	47.71	49.16	3.04
7	44	47.59	8.16	44	45.45	3.3
8[a]	46.39	49.98	7.74	46.39	47.84	3.13
8[b]	47.23	50.82	7.6	47.23	48.68	3.07
8[c]	40.34	43.93	8.9	40.34	41.79	3.59
8[d]	40.91	44.5	8.78	40.91	42.36	3.54
9	U/A	U/A	U/A	U/A	U/A	U/A
10	42.98	46.57	8.35	42.98	44.43	3.37
11	41.39	44.98	8.67	41.39	42.84	3.5
12 (Part-Syn)	49.84	53.43	7.2	49.84	51.29	2.91
12 (100% Syn)	57.79	61.38	6.21	57.79	59.24	2.51

a - Conventional petroleum based jet fuel
b - Oil Shale, Australia (% Nitrogen content unknown)
c - Oil Shale, Australia (Low Nitrogen)
d - Oil Shale, Australia (High Nitrogen)
U/A - Unavailable

Table 14. Non-weighted Cetane Index of JP-8 versus 50/50-ATJ/JP-8 – CRC Dataset

PADD Region	CI (D4737-10)			CI (D976-06 (2011))		
	JP-8	50/50 ATJ/JP-8	% Increase	JP-8	50/50 ATJ/JP-8	% Increase
1	47.32	50.91	7.59	47.32	48.77	3.06
2	45.32	48.91	7.92	45.32	46.77	3.2
3	40.78	44.37	8.8	40.78	42.23	3.56
4	U/A	U/A	U/A	U/A	U/A	U/A
5	47.38	50.97	7.58	47.38	48.83	3.06

U/A - Unavailable

The dataset from CRC Report No. 647 contained a few fuel sample sets and therefore statistical quantities were not computed and plotted. The CI values were calculated from distillation data and density in the report. The overall conclusion is that the CI values increase between 7% to 8% for maximum ATJ blend when four variable CI ASTM D4737 method is used and the increase is a around 3% when CI is computed using ASTM D976 method, for all three jet fuels. This conclusion is consistent with the overall increase in CI values obtained using the PQIS data set.

5.3 MAXIMUM ATJ BLEND CETANE PROPERTIES FOR TRI-SERVICES DATASET

The Tri-Services dataset contains all the cetane properties, including DCN and CN values, in addition to CI data from both ASTM D4737 and ASTM D976 methods, for Jet A and JP-8 fuel. In addition to CI predictions of maximum ATJ blends, projections could also be made for CN and DCN properties. The most vital information being the percentage volume of ATJ that can be blended in to result in a minimum DCN or CN value of 40, for each PADD region. A comparison of cetane properties for neat fuels and maximum ATJ blends are shown in Table 15 and Table 16, for Jet A and JP-8 fuels, respectively.

Table 15. Non-weighted Cetane Properties of Jet A versus 50/50-ATJ/Jet A – Tri-Services Dataset

PADD Region	CI (D4737-10)			CI (D976-16 (2011))			DCN			CN		
	Jet A	50/50 ATJ/Jet A	% Change	Jet A	50/50 ATJ/Jet A	% Change	Jet A	50/50 ATJ/Jet A	% Change	Jet A	50/50 ATJ/Jet A	% Change
1	47.71	51.3	7.52	47.71	49.16	3.04	45.70	35.17	-23.05	48.50	33.19	-31.57
2	44	47.59	8.16	44	45.45	3.3	39.90	29.37	-26.40	39.40	24.09	-38.86
3	46.39	49.98	7.74	46.39	47.84	3.13	50.10	39.57	-21.03	49.30	33.99	-31.05
4	47.23	50.82	7.6	47.23	48.68	3.07	44.90	34.37	-23.46	44.00	28.69	-34.80
5	40.34	43.93	8.9	40.34	41.79	3.59	43.80	33.27	-24.05	43.50	28.19	-35.20

Table 16. Non-weighted Cetane Properties of JP-8 versus 50/50-ATJ/JP-8 – Tri-Services Dataset

PADD Region	CI (D4737-10)			CI (D976-16 (2011))			DCN			CN		
	JP 8	50/50 ATJ/JP-8	% Change	JP-8	50/50 ATJ/JP-8	% Change	JP-8	50/50 ATJ/JP-8	% Change	JP-8	50/50 ATJ/JP-8	% Change
1	47.74	51.33	7.52	46.23	47.68	3.14	45.70	35.17	-23.05	45.40	30.09	-33.72
2	47.14	50.73	7.62	46.38	47.83	3.13	49.70	39.17	-21.20	47.40	32.09	-32.30
3	49.27	52.86	7.29	47.52	48.97	3.05	45.90	35.37	-22.95	46.10	30.79	-33.21
4	44.33	47.92	8.10	43.15	44.60	3.36	42.30	31.77	-24.91	43.00	27.69	-35.60
5	44.68	48.27	8.03	42.74	44.19	3.39	46.40	35.87	-22.70	43.00	27.69	-35.60

It should be noted that the percentage change in CI values for both Jet A and JP-8, was between 7% to 8% using ASTM D4737, and around 3% using ASTM D976 method, which is consistent with PQIS and CRC data sets. The additional information that can be inferred from the results is that there is a drastic decrease in CN and DCN values for maximum ATJ blends. The decrease in DCN varies between 20% to 25%, while the decrease in CN varies between 30% to 35%. As a result the CN and DCN values for some PADD regions fall much below than the prescribed value of 40. In PADD 2, for Jet A, the maximum ATJ blend has a DCN value of 29.37, while PADD 4 performs poorly with a DCN value of 31.77. Therefore, it is strongly recommended that maximum ATJ blends should not be used for Army ground equipment.

The maximum volume percentage of ATJ in the blend that yields a CN or DCN value of 40, was determined for each PADD, based on the correlation equations that were developed in Section 4.0 and the results are listed in Table 17.

Table 17. Maximum Allowable Volume Percent of ATJ in Fuel Blend

PADD Region	Jet A		Jet A		JP-8		JP-8	
	Max vol.% ATJ	DCN	Max vol.% ATJ	CN	Max vol.% ATJ	DCN	Max vol.% ATJ	CN
1	32.00	40.17	30.00	40.03	32.00	40.17	20.00	40.00
2	0.00	39.90	0.00	39.40	47.00	40.09	26.00	40.19
3	48.00	40.19	32.00	40.19	33.00	40.13	22.00	40.10
4	29.00	40.07	15.00	40.04	16.00	40.07	11.00	40.15
5	24.00	40.05	13.00	40.10	35.00	40.13	11.00	40.15

For Jet A fuel, in PADD 2, the CN and DCN values of neat fuel are approximately equal to 40, and therefore, Jet A obtained from PADD 2 is not qualified to make a blend, as it would further reduce the CN/DCN values. While on the other hand, PADD 3 is best suited to make fuel blends with maximum volume percentage of ATJ, as high as 48-vol.% of ATJ. For CN values of Jet A, PADDs 4 and 5 can take the least amount of ATJ in the fuel to get a CN value around 40, while PADDs 1 and 3 can take twice the volume of ATJ to reach the same value. For JP-8 fuel, PADDs 1, 3 and 5, takes around 30-vol% of ATJ to reach a DCN value of 40. PADD 2 can take as high as 47-vol%, while PADD 4 takes around 16-vol% to each the same value. For all the PADDs, it takes between 10-vol% and 25-vol% for CN values to drop closer to 40. Overall, for all practical purposes, it can be concluded that maximum ATJ blends can be made from PADD 3 for Jet A fuel , and PADD 2 for JP-8 fuel.

6.0 CONCLUSIONS

The overall conclusion is that maximum ATJ blends from any jet fuel (Jet A, Jet A-1, and JP-8) had an increase in CI from 7% to 8% using the four variable, ASTM D4737 method, while the increase in CI was approximately 3% using ASTM D976 method. These values were consistent in all the literature datasets, spanning from 2006 to 2014, that were reviewed and examined. Based on the extensive decrease in CN and DCN values much below 40, it is recommended that maximum ATJ blends (50/50 ATJ/Jet fuel blends) not be used in Army equipment with diesel engines. Calculations were made for the volume percentage of ATJ that can be blended into jet fuel for each PADD region in CONUS to result in a CN or DCN value of 40. This formed the recommendation for achieving maximum ATJ blends that are deemed fit-for-use in ground equipment. Additionally, it was highlighted that Jet A obtained from PADD 2 is not qualified to make an ATJ blend. For all practical purposes, it was concluded that maximum ATJ blends can be made from PADD 3 for Jet A fuel , and PADD 2 for JP-8 fuel, without greatly compromising the overall combustion quality.

7.0 REFERENCES

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